Technical Note

Inception Point for Embankment Dam Stepped Spillways

Sherry L. Hunt, M.ASCE[1]; and Kem C. Kadavy, P.E.[2]

Abstract: Retrofitting embankment dams with stepped spillways has become a common design practice, particularly for those dams that change hazard classification from low to high. For embankment dams retrofitted with stepped spillways, the chute length is often insufficient for developing aerated flow or an inception point. The inception point is a key spillway design parameter used in energy dissipation, flow depth, and air entrainment prediction relationships. Original research for developing an inception-point relationship for stepped spillways was based on primarily gravity ($\theta \geq 26.6°$) stepped spillways, with the majority having an ogee crest control section. The resulting, inception-point relationship tends to overestimate the inception-point location for broad-crested weir stepped spillways ($\theta \leq 26.6°$) when the Froude surface roughness (F_*) is less than 10. Consequently, research on broad-crested weir stepped spillways retrofitted for embankment dams has been conducted to provide an optimized inception-point relationship. This study provides additional data allowing further refinement (i.e., $F_* \leq 28$) of the inception-point relationship for broad-crested stepped spillways ($\theta \leq 26.6°$), and it provides a new relationship for broad-crested weir stepped spillways for $F_* > 28$. **DOI: 10.1061/(ASCE)HY.1943-7900.0000644.** © *2013 American Society of Civil Engineers.*

CE Database subject headings: Roller-compacted concrete; Dam safety; Embankment dams; Energy dissipation; Aeration; Air entrainment; Spillways; Rehabilitation.

Author keywords: Roller-compacted concrete; Dam safety; Dams; Embankment; Energy dissipation; Aeration; Air entrainment; Spillways; Rehabilitation; Inception point.

Introduction

Urban sprawl in the vicinity of embankment dams has led to hazard classification changes for many dams worldwide. One of the more significant deficiencies in these reclassified dams is inadequate spillway capacity, which can result in embankment overtopping. Roller-compacted concrete (RCC) stepped spillways has become a preferred method for providing overtopping protection and increased spillway capacity for these dams. An increased demand for stepped spillways applied to embankment dams has led to increased research efforts regarding flow properties on stepped spillways. Consequently, research findings defining such things as air entrainment, characteristic flow depths, velocity, and energy dissipation downstream of the inception point, the location where the turbulent boundary layer reaches the free surface, are more readily available in literature (Chanson 1994, 2002; Chamani and Rajaratnam 1999; Matos et al. 2002; Boes and Hager 2003a, b; Gonzalez 2005; Gonzalez and Chanson 2007; Meireles and Matos 2009; Hunt and Kadavy 2010a, b, c, 2011; Bung 2011; Pfister and Hager 2011). Hunt and Kadavy (2010a, b, c, 2011) and Meireles and Matos (2009) have indicated that the inception point is valuable in defining flow depth and energy dissipation in stepped spillways. Fig. 1 illustrates the location of the inception point with bulked or aerated flow expected downstream of the inception point. Bulked flow as it relates to air entrainment is defined as increased flow depth due to the presence of air.

Scientists at the USDA-Agricultural Research Service (ARS) Hydraulic Engineering Research Unit (HERU) in Stillwater, Oklahoma, have conducted research to develop generalized stepped spillway design criteria for spillways with slopes $\theta \leq 26.6°$. The research utilizes a large-scale testing facility over a broad range of discharges and step heights. Inception-point location, flow depth, velocity, air entrainment, and energy dissipation are important aspects for the design of stepped spillways. The objective of this paper is to discuss the inception-point relationships developed from this research program. This research will provide engineers with useful and practical design guidance for stepped spillways.

Background

Wood et al. (1983) were the first to propose an inception-point relationship for plane chute spillways with ogee-crested spillway entrances. Similar to Wood et al. (1983), Chanson (1994, 2002) developed a surface inception point relationship for stepped spillways, with the majority having ogee-crested weirs, slopes steeper than 26.6°, and Froude surface roughness $F_* > 1$. Meireles and Matos (2009) and Hunt and Kadavy (2011) recognized that Chanson (1994, 2002) overestimates L_i for $F_* \leq 10$. Meireles and Matos optimized Chanson's relationship for broad-crested weir stepped spillways retrofitted for embankment dams, but the relationship is only valid for $1.9 \leq F_* \leq 10$. Hunt and Kadavy (2011) further optimized Chanson's (1994, 2002) inception-point relationship to be applicable for broad-crested weir stepped spillways with slopes as flat as 14° when $1 \leq F_* \leq 100$, but they recommended further validation at additional slopes.

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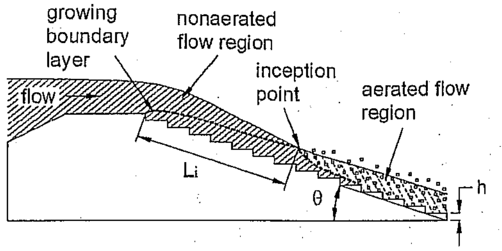

Fig. 1. Schematic of the inception point in relation to the stepped spillway

Experimental Setup

Froude similitude is the most commonly chosen method for modeling free surface flows because gravitational forces typically dominate. For highly air-entrained flows, viscous forces and surface tension become more dominant and must be considered in model development; otherwise, distortions may be introduced in the data if these secondary forces are ignored. Chanson (2002) recommends a model scale larger than 10:1 (model dimensions greater than 0.1 times the prototype dimensions). Boes and Hager (2003b) and Pfister and Hager (2011) state a minimum Reynolds number (R) > 10^5 and a Weber number (W) > 100 allows for scale effects to be excluded. Takahashi et al. (2006) recommends that Froude, Reynolds, and Morton numbers similarity be satisfied, but they recognized this can only be achieved at full scale.

To develop a better understanding of the inception point, energy dissipation, velocity, air entrainment, and flow depth in embankment dam stepped spillways (typically $\theta \leq 26.6°$), researchers at the USDA-ARS HERU constructed a state-of-the-art testing facility for developing practical design guidelines for stepped spillways. To minimize scale effects, the results from the stepped spillway tests conducted in this facility are considered applicable for scales 10:1 or larger. The model facility also meets recommendations set forth by Boes and Hager (2003b) with Weber and Reynolds numbers reported no lower than 177 and 1.38×10^5, respectively.

A concrete flume approximately 1.8 m wide with a 18.4° slope and a 3-m-long broad-crested weir was constructed for a two-dimensional stepped spillway model. Fig. 2 illustrates a schematic of the stepped spillway model. With a maximum head of 1 m tested, the weir is classified as broad-crested according to Chow (1959) because the head on the weir is less than 1.5 times the weir length. The broad-crested weir was calibrated to determine flow discharge. Discharge was monitored during testing using two methods: (1) a combination of a gage well and manually operated point gage and (2) a string potentiometer coupled with a computer-interfaced data acquisition system. Flow to the flume was introduced by a gravity flow vegetated channel. Water to the channel was supplied by five 0.46-m-diameter siphons located at Lake Carl Blackwell Dam. This system provides a maximum discharge of 3.4 m^3/s.

The flume has 5.5 m of vertical drop and was originally constructed with a plane, rough concrete surface. According to Chow (1959), a concrete surface has an approximate roughness height between 0.46 and 3 mm. For this study, the plane, rough concrete surface was assumed to have an equivalent step height = 0.46 mm. Along with the plane, rough concrete surface tested, steps having a height of 19, 40, 76, 152, and 305 mm were tested. A total of 54 tests were conducted over unit discharges ranging between 0.15 and 1.9 $m^3/s \cdot m$, as summarized in Table 1.

The surface inception point was observed visually and recorded photographically, defining operationally the inception point as the horizontal distance from the downstream edge of the spillway crest to the point where white water first appeared across the full width of the free surface. This distance was then converted to a corresponding L_i, as defined in Fig. 1.

Table 1. Summary of Unit Discharge (q), Step Height (h), and Inception Point (L_i) for a 18.4° Chute Slope Stepped Spillway

q ($m^3/s \cdot m$)	h (mm)	L_i (m)	q ($m^3/s \cdot m$)	h (mm)	L_i (m)
0.152	0.46	4.0	0.150	76	1.4
0.321	0.46	7.3	0.338	76	3.14
0.458	0.46	10	0.464	76	3.87
0.627	0.46	12	0.634	76	5.06
0.779	0.46	15	0.813	76	6.28
0.948	0.46	18	0.975	76	7.22
1.25	0.46	none[a]	1.27	76	8.69
1.56	0.46	none[a]	1.59	76	10.6
1.84	0.46	none[a]	1.87	76	11.3
0.159	19	2.7	0.154	152	0.98
0.348	19	4.57	0.337	152	2.4
0.484	19	5.79	0.475	152	3.38
0.645	19	6.74	0.623	152	4.33
0.822	19	7.71	0.795	152	5.30
0.975	19	8.93	0.948	152	6.28
1.26	19	10.6	1.24	152	7.47
1.61	19	13.0	1.57	152	8.93
1.87	19	14.9	1.84	152	10.1
0.156	40	2.2	0.146	305	0.98
0.342	40	3.63	0.330	305	1.7
0.487	40	5.06	0.461	305	2.4
0.637	40	5.79	0.619	305	2.9
0.818	40	7.22	0.799	305	3.87
0.985	40	8.44	0.948	305	4.82
1.26	40	10.1	1.24	305	5.30
1.60	40	12.3	1.58	305	6.28
1.88	40	13.5	1.79	305	6.74

[a]No inception point was observed for the length of chute in the study.

Results and Discussion

Throughout this study, photographs were taken to document the changes in the spillway flow appearance as it descended the chute. Visual observations along with the photographic records were used to determine the surface location of the inception point for each flow rate and step-height configuration. Table 1 summarizes the

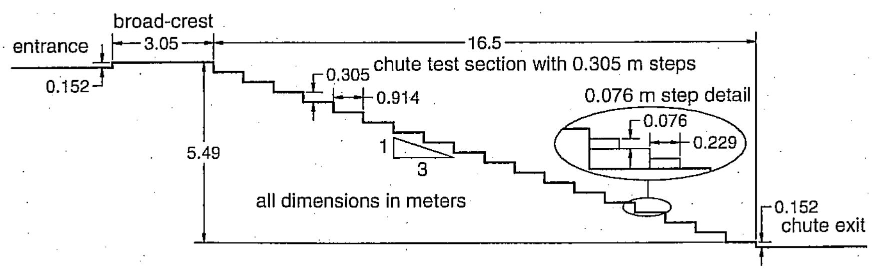

Fig. 2. Schematic of stepped spillway model

q, h, and L_i for the 18.4° stepped spillway model. A degree of uncertainty is expected by visually inspecting the surface location of L_i, but provides a practical approach for determining L_i in models and in prototype stepped spillways.

Fig. 3 illustrates Hunt and Kadavy's (2011) data and present study data along with the relationship proposed by Hunt and Kadavy (2011). Most notably, Fig. 3 reveals that when $F_* > 100$, the data do not align with Hunt and Kadavy's (2011) relationship. A more detailed curve fitting analysis reveals that the point at which the smaller F_* trend deviates from the larger F_* trend is $F_* = 28$. The data representing $28 < F_* < 10^5$ are data from the 0.46 mm (i.e., plane, rough concrete surface), 19 mm, 40 mm, and some 76 mm step height model tests. For $28 < F_* < 10^5$, the small steps no longer perform like steps but perform more like a rough surface, and this change can significantly affect the surface location of the inception point. Because of the deviation, data from Hunt and Kadavy (2011) and the present study were fitted with Eqs. (1) and (2) for $0.1 < F_* \leq 28$ and $28 < F_* < 10^5$, respectively, as illustrated in Fig. 3.

$$\frac{L_i}{k_s} = 5.19(F_*)^{0.89} \qquad 0.1 < F_* \leq 28 \qquad (1)$$

$$\frac{L_i}{k_s} = 7.48(F_*)^{0.78} \qquad 28 < F_* < 10^5 \qquad (2)$$

where L_i = distance from the downstream edge of the broad-crested weir to the surface inception point; θ = chute slope; F_* = Froude number defined in terms of roughness height, $F_* = q/[g(\sin\theta)k_s^3]^{0.5}$; q = unit discharge; g = gravitational constant, k_s = surface roughness = $h\cos(\theta)$; and h = step height. The coefficients of determination, R^2, for each relationship are 0.993 and 0.999, respectively. These relationships are a best fit of the data for the corresponding F_* range, and they result in a smooth transition between the two relationships. The standard errors of estimate in L_i/k_s for Eqs. (1) and (2) are 2.8 and 290, respectively.

L_i data reported by Chanson and Toombes (2002), Gonzalez (2005), Chanson and Carosi (2007), Felder and Chanson (2008), Hunt and Kadavy (2011), and the present study are illustrated in Fig. 4(a). Each of these studies represent stepped spillway slopes typical of embankment dams and F_* within the range recommended by Eq. (1). Fig. 4(a) shows good agreement between the data presented by Chanson and Toombes (2002), Gonzalez (2005), and Chanson and Carosi (2007) and Eq. (1). Some variability from Eq. (1) is noted from data reported by Felder and Chanson (2008) and Gonzalez (2005). This variability may be related to (1) effects related to intake conditions (i.e., pressurized versus uncontrolled) as described by Chanson (2006), (2) differences between the scale of the models and the range and magnitude of q and h reported, or (3) the subjectivity of where the inception point occurs. For the present study and Hunt and Kadavy (2011), q ranged from 0.11 to 1.9 $m^3/s \cdot m$ and h ranged from plane, rough concrete to 305 mm, while Felder and Chanson (2008) and Gonzalez (2005) reported q ranging from 0.05 to 0.2 $m^3/s \cdot m$ and h ranging from 50 to 100 mm. All the models described by the other researchers presented in Fig. 4(a) are quite small in comparison to the models represented in this present study and described by Hunt and Kadavy (2011), yet the data agree fairly well. Another factor that may explain the variability may be the subjectivity of the inception point as observed by the various researchers. Data in this present study were recorded for a broad range of h and q as well as by the same researchers; thereby, precision and consistency of the measurements are likely improved over the smaller subset of data available from smaller scale models.

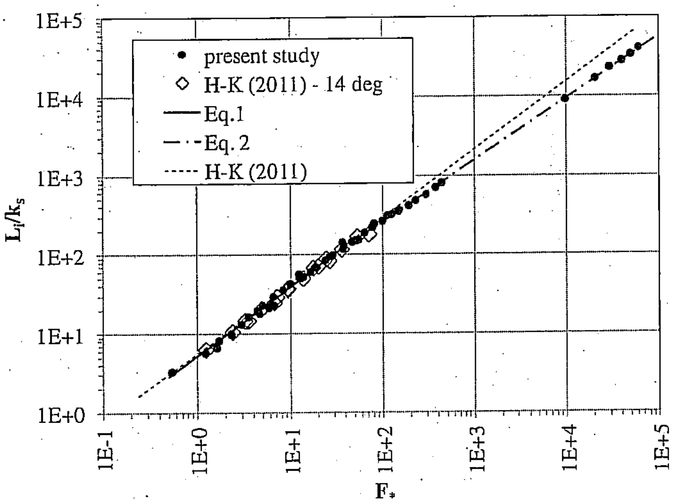

Fig. 3. Normalized inception point data from Hunt and Kadavy (2011) and the present study as it relates to Hunt and Kadavy's (2011) relationship solved for $\theta = 18.4°$ and Eqs. (1) and (2)

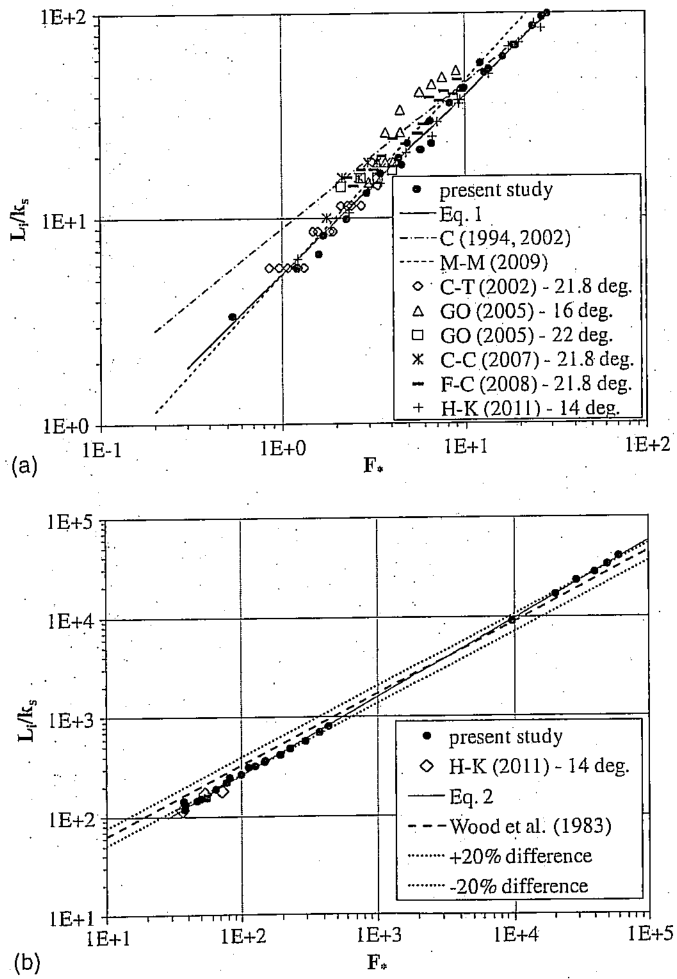

Fig. 4. (a) Eq. (1) and Chanson's (1994, 2002) and Meireles and Matos's (2009) relationships compared to normalized inception point data from literature and the present study; (C = Chanson; C-T = Chanson and Toombes; GO = Gonzalez; C-C = Chanson and Carosi; F-C = Felder and Chanson; H-K = Hunt and Kadavy; M-M = Meireles and Matos); (b) Eq. (2) compared to normalized inception point data from the present study and Hunt and Kadavy (2011) and with Wood et al.'s (1983) relationship

Fig. 4(a) also illustrates Eq. (1) in comparison to Chanson's (1994, 2002) and Meireles and Matos's (2009) relationships. Chanson's (1994) relationship represents studies primarily for steep-sloped, ogee-crested weir stepped spillways. Meireles and Matos (2009) developed their relationship for broad-crested stepped spillways typically applied to embankment dams. Comparing Chanson's relationship and data in this present study along with those reported by Chanson and Toombes (2002), Gonzalez (2005), Chanson and Carosi (2007), Felder and Chanson (2008), and Hunt and Kadavy (2011) shows a breakdown in the fit of his relationship to the data when $\mathsf{F}_* \leq 10$. The relationship presented by Meireles and Matos (2009) fits the data quite well for its developed range of $1.9 \leq \mathsf{F}_* \leq 10$. Their relationship begins to deviate from the data as it extended beyond its recommended range for $\mathsf{F}_* > 10$. Because Eq. (1) was developed over a broader range of h and q, at a larger scale, and validated by a subset of data reported in literature, Eq. (1) is recommended for determination of L_i/k_s for stepped spillways having a broad-crested weir for $0.1 < \mathsf{F}_* \leq 28$.

Wood et al.'s (1983) relationship was used to validate Eq. (2). The primary differences between Wood et al.'s (1983) relationship and Eq. (2) are (1) Wood et al. (1983) developed their relationship for ogee-crested plane spillways while Eq. (2) was developed for broad-crested plane, rough spillways, (2) Wood et al.'s (1983) relationship was based on a theoretical development rather than empirically based like that of Eq. (2), and (3) the slope term, $\sin\theta$, is omitted from Eq. (2) because it was viewed to have very little influence on the determination of L_i/k_s for the chute slopes tested. Fig. 4(b) compares Wood et al.'s (1983) relationship and Eq. (2) to the data of the present study and data from Hunt and Kadavy (2011) for $28 < \mathsf{F}_* < 10^5$. Eq. (2) is a best fit of the data. The experimental results fall within an uncertainty band of $\pm 20\%$ relative to Wood et al.'s (1983) relationship. The differences between Wood et al.'s (1983) relationship and the experimental results are likely due to crest types (broad-crest versus ogee) and the increased surface roughness by the inclusion of steps.

Conclusions

L_i data from an 18.4° sloped stepped spillway model closely align with the L_i relationship developed by Hunt and Kadavy (2011) for a 14° chute slope stepped spillway when $\mathsf{F}_* \leq 100$. Incorporating the data from the present study for small to no steps in relation to large discharges, the need to further optimize Hunt and Kadavy's (2011) relationship into multiple best-fit relationships representing $0.1 < \mathsf{F}_* \leq 28$ and $28 < \mathsf{F}_* < 10^5$, respectively, became apparent. Supporting data from Chanson and Toombes (2002), Gonzalez (2005), and Chanson and Carosi (2007) validates Eq. (1). Data reported by Felder and Chanson (2008) along with some data from Gonzalez (2005) show variability from Eq. (1). The precision of the measurements from the larger-scale model described in the present study likely decreases variability between the data and prediction relationships, whereas smaller models as described by Gonzalez (2005) and Felder and Chanson (2008) over a more limited range of step heights and flow discharges may contribute to variability in the data in comparison to Eq. (1). Additionally, intake conditions as detailed by Chanson (2006) and the subjectivity of the recorded data lead to variability in the data.

Wood et al.'s (1983) relationship closely aligns with Eq. (2) as shown in Fig. 4(b), yet $\pm 20\%$ difference between the experimental results and Wood et al.'s (1983) could be expected with the step roughnesses evaluated in this present study. Eq. (2) is recommended for determination of L_i/k_s for stepped spillways having a broad-crested weir for $28 < \mathsf{F}_* < 10^5$. Although Wood et al.'s (1983) relationship was developed theoretically for ogee-crested, plane spillways, it provides a reasonable solution for determining L_i/k_s for stepped spillways having a broad-crested weir for $28 < \mathsf{F}_* < 10^5$.

L_i is important for other design parameters like energy dissipation and flow depth (Meireles and Matos 2009; Hunt and Kadavy 2010a, b, c, 2011). If applied appropriately to minimize scale effects (i.e., scales 10:1 or larger), this research will advance the development of practical design guidelines for stepped spillways retrofitted to embankment dams.

Notation

The following symbols are used in this paper:

F_* = Froude number defined in terms of the roughness height: $\mathsf{F}_* = q/\sqrt{g(\sin\theta)k_s^3}$;
g = gravitational constant;
h = step height;
k_s = surface roughness = $h\cos(\theta)$;
L_i = distance from the downstream edge of the broad-crested weir to the surface inception point;
q = unit discharge;
R = Reynolds number;
W = Weber number; and
θ = channel slope.

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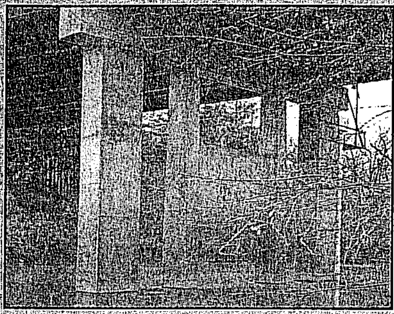

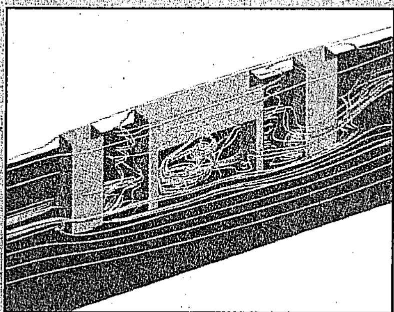

Technical Papers

Technical Notes

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